Wright Aeronautical Serial Report No. CTR.00-272

Final Report

ADVANCED HEAT TRANSFER ELEMENTS FOR LIQUID METAL REGENERATOR SYSTEMS

April 30, 1963

Wright Aeronautical Division

Copy 15 of 50

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Final Report

ADVANCED HEAT TRANSFER ELEMENTS FOR LIQUID METAL REGENERATOR SYSTEMS

In Fulfillment of Item 8 Contract NOw 62-0601C

with

Department of the Navy
Bureau of Naval Weapons
Washington 25, D.C.

April 30, 1963

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I INTRODUCTION

This report summarizes the work accomplished on the feasibility of extending the materials and design restrictions of current finned tube heat transfer elements to provide lighter weight, higher performance liquid metal regenerator systems. Under this program the following items were investigated:

(a) Fin Design - The feasibility of fabricating tapered fins and fins with a fin-to-tube diameter ratio greater than 2.0:1.

(b) Fin Material - The feasibility of using a material requiring no cladding or protective coating.

(c) Fin Protection - The feasibility of reducing the protective cladding by means of coatings, platings, etc.

(d) Fin Thickness - The feasibility of reducing the total fin thickness to .003".

Metallurgical, analytical, and fabrication studies performed show that significant improvements in heat exchanger weight can be achieved by the use of finned tubes made with extended surfaces of aluminum bronze. The properties of aluminum bronze which provide improved performance heat exchanger surfaces are as follows:

(a) Excellent oxidation resistance, and therefore, cladding is not required.

(b) Excellent ductility which makes possible the fabrication of fins with thicknesses of .003" or less.

(c) High conductivity.

Sample finned tube elements made from aluminum bronze fins were developed, and a small heat exchanger core was fabricated to demonstrate feasibility of the method.

On the basis of advanced 4000 H.P. shaft engines, improvements of 20 to 30% in core weight of liquid metal regenerator systems is indicated with the heat transfer elements developed.

II BACKGROUND

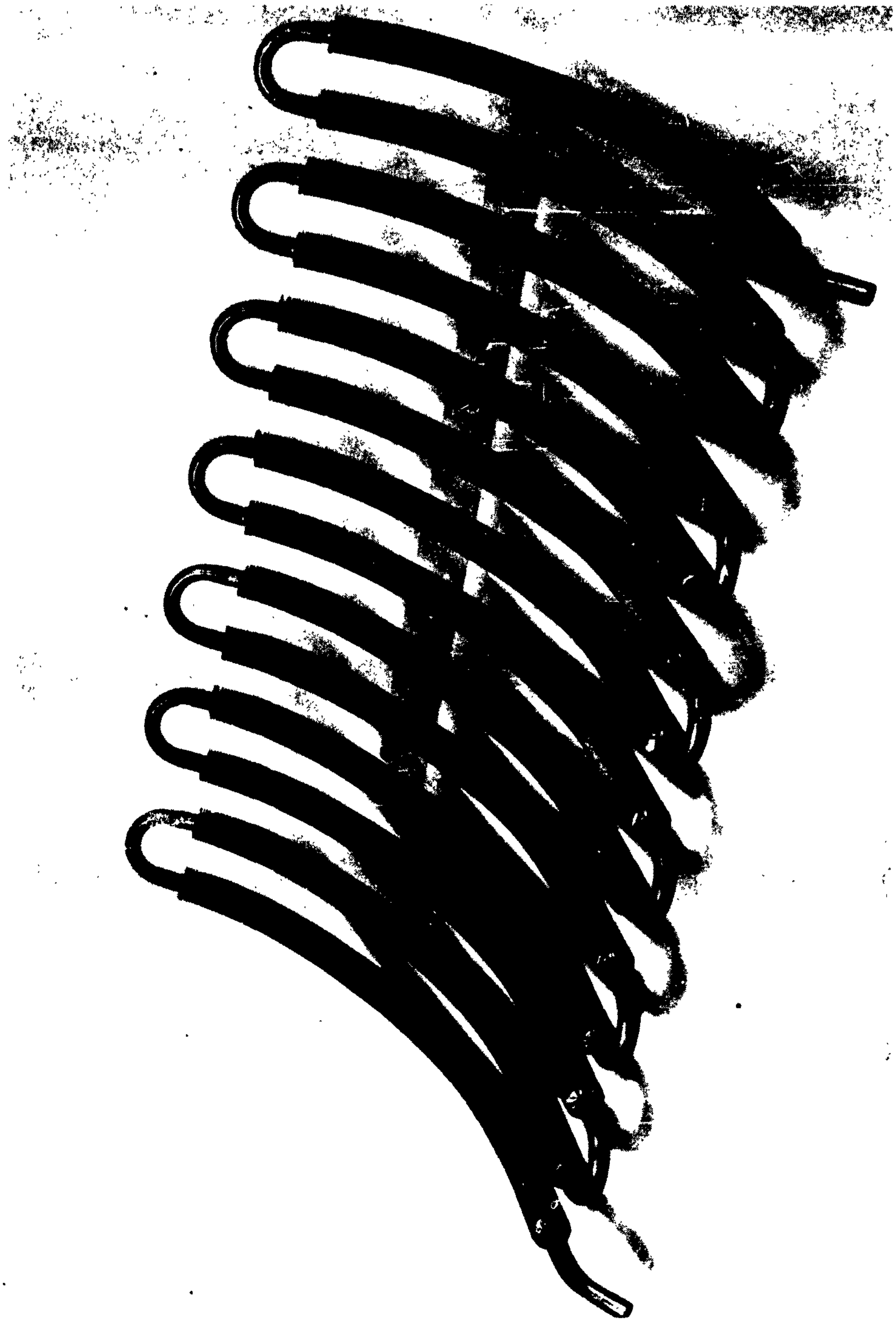
The function of a liquid metal regenerator system for turboprop engines is to reduce fuel consumption to the extent that the added weight of the system is more than offset by the weight of fuel saved during the mission of the aircraft. A liquid metal regenerator system consists of a heat exchanger to extract heat from the turbine exhaust, a heat exchanger to release heat to the compressor air prior to its entry to the combustor, and a circulating liquid metal system to convey heat from the turbine heat exchanger to the compressor heat exchanger.

The heat exchangers are comprised of heat transfer elements joined to collecting headers. The heat transfer elements are the active portion of the system and constitute the major portion of the weight of the system. Improvement in the performance versus weight of these elements will directly improve the effect of the liquid metal regenerator system on the engine. Therefore, efforts have been directed towards developing advanced heat transfer elements specifically suited for liquid metal regenerator service.

The heat transfer elements used to make the heat exchangers in the liquid metal regenerator system, evaluated and developed under a separate portion of this contract, represent the latest advances of the art. These heat transfer elements are finned tubes arranged in a serpentine fashion and are hereby described to serve as a reference for the work covered under this portion of the contract.

Tube O.D.	.188 inch
Tube Wall	.015 inch
Fin O.D.	.375 inch
Fins per inch	30
Total fin thickness	.005 inch
Tube material	316 stainless steel
Fin material	Stainless steel clad high conductivity copper
Copper thickness	.0025 inches

The fins are positioned by shallow grooves in the tube and are bonded to the tubes by a nickel base braze. The braze material is sprayed onto the tubes after the fins have been wound. Braze is deposited on the edge of the fin to protect the exposed edge of the clad copper and deposited on the tube at the base of the fins to form a thermal bond between the fins and the tube. The tubes are bent into serpentines and the serpentines further bent to suit the heat exchanger configuration prior to brazing in controlled atmosphere furnace. A typical serpentine heat transfer element for an axial flow compressor heat exchanger is shown in Figure 2-1. The plane of the serpentine is bent to an involute curve to obtain constant tube spacing throughout the annular cross sectional area of the heat exchanger.



HEAT TRANSFER ELEMENT FOR TURBINE HEAT EXCHANGER

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Figure 2-1

III DESCRIPTION OF WORK

Efforts to reduce weight and increase performance of finned tube heat transfer elements have been directed to: (1) optimization studies, (2) metallurgical studies, and (3) fabrication studies. These efforts have terminated in the fabrication of a full scale sample heat exchanger, demonstrating feasibility of manufacture of advanced finned tube heat transfer elements.

Preliminary screening of performance, metallurgical and fabrication characteristics led to the selection of coated copper fins and unprotected aluminum bronze fins as the most promising materials for investigation. Optimization studies were made on both these fin materials with reasonable allowances for oxidation protection of the copper fins. A cursory examination revealed that increasing gains in performance and weight reduction could be made by going to smaller and smaller tube and fin diameters. However, these investigations were limited to diameters considered feasible for heat transfer elements capable of manufacture and use in the immediate future. Studies were made for real heat exchangers as applied to a 3750 HP turboprop study engine rather than by separate treatment of various parameters.

IV OPTIMIZATION STUDIES

Finned tube serpentine heat transfer elements are considered most suitable for liquid-metal-coupled applications when compared to other conventional types such as plain tube banks and plate-fin combinations primarily because of their: (1) adaptability to approach counterflow conditions; (2) high ratio of gas side surface area to liquid metal surface area; (3) high ratio of gas side volume to liquid metal volume; (4) flexibility to accommodate large thermal gradients; and (5) flexibility of arrangement.

While it is true that other types of surfaces can achieve some of the above advantages, it is felt that the finned tube serpentine is the only type which can be optimized, independently, in each of the five areas enumerated above.

Selection of an optimum core of the finned tube type requires establishing the most desirable values for the following four geometric parameters:

(1) Outside fin diameter
(2) Outside tube diameter
(3) Fin thickness
(4) Number of fins per inch

In order to establish the optimum core configuration for the study engine and to thereby, generate design goals for mechanical and metallurgical feasibility studies, an analysis was conducted using electronic data processing methods in which heat exchanger core geometry was systematically varied while maintaining constant heat exchanger inlet conditions and constant heat exchanger performance i.e., overall effectiveness, ratio of component effectiveness, overall pressure drop and ratio of pressure drops.

Heat exchanger performance parameters were selected as:

$$E_o = 70\%$$

$$E_h/E_c = 1.0$$

$$(\Delta P/P)_c = .02$$

$$(\Delta P/P)_h = .02$$

where

E_o = Overall Effectiveness

E_h = Turbine (Hot Side) Heat Exchanger Effectiveness

E_c = Compressor (Cold Side) Heat Exchanger Effectiveness

$(\Delta P/P)_c$ = Compressor Heat Exchanger Pressure Drop Relative to Inlet Pressure

$(\Delta P/P)_h$ = Turbine Heat Exchanger Pressure Drop Relative to Inlet Pressure

The parameters investigated were:

(1) Tube O.D.; .1875 in. and .15625 in.
(2) Ratio of fin O.D. to tube O.D.; 2.0, 2.5 and 3.0.
(3) Overall fin thickness; .0025 in., .003 in., .004 in. and .005 in.

It had previously been established that the number of fins per inch should be maintained as high as practical. (TREC Report 61-46, "Liquid Metal Regenerator Feasibility Study for a Light Weight Turbo-shaft Engine".) However, the ability to operate at engine conditions without fouling has not been investigated beyond 30 fins per inch. This parameter was, therefore, maintained at 30 fins per inch for all configurations. Tube wall thickness was also maintained at .015 inches.

Each combination of these parameters was investigated utilizing two basically different fin materials: (1) a solid aluminum bronze alloy requiring no additional surface protection and (2) solid copper having .0005 inches of nickel plate on all exposed surfaces. The fin thickness in both cases was the overall thickness including the nickel plate in the latter case.

The results of this analysis in terms of core weight versus effectiveness are shown on Figures 4-1 through 4-8.

For comparison, the present state-of-the-art fins (.375 O.D., .005" thick with .0025 clad and 2.0 diameter ratio) are shown (*) on the same plots as the advanced types.

Since this was an optimization study for fin geometry and would not necessarily give the same results for both exchangers, the results are presented separately for the turbine heat exchanger and the compressor heat exchanger. The results indicate the following:

(1) For the same diameter ratio, fin thickness and tube O.D., the plated copper fin configuration resulted in lighter core weights than did the aluminum bronze fins for both the compressor exchanger and the turbine exchanger.

(2) For the same fin thickness and fin material the smaller tube diameter resulted in lower weights for both heat exchanger cores.

(3) The minimum thickness investigated resulted in minimum core weights for each combination of the other parameters. It is felt, therefore, that fabrication techniques will be the controlling factor in this area, rather than heat transfer requirements.

(4) In general, a diameter ratio of 2.0 resulted in lowest core weight for the compressor heat exchanger and a diameter ratio of 2.5 resulted in lowest core weight for the turbine heat exchanger. This was true for both tube diameters investigated and for both the plated copper fin and the aluminum-bronze fin.

(5) For the turbine heat exchanger, the thinnest fins investigated appear to be farther from optimum than for the compressor heat exchanger. This results from the lower heat transfer coefficient in the turbine exchanger, which in turn results in higher fin efficiencies for the same thickness fin than in the case of the compressor heat exchanger.

(6) At an overall fin thickness of .005" there is not a significant advantage for either the aluminum bronze fin or the plated copper fin over the clad copper fin. However, the .005 inch clad copper fin is approaching the limit of manufacturing feasibility for this type of configuration, whereas it appears quite feasible at this time to produce fins .003 inch thickness of the other two configurations. The .005 inch clad copper fin should not, therefore, be compared to a similar thickness fin, but should be compared on the basis of similar manufacturing feasibility, to fins of the other configurations having thicknesses of .003 inches or less. On this basis, either the aluminum bronze fins or the plated copper fins are clearly superior inasmuch as for .003 inches thickness they result in heat exchanger core weights which are from 14 to 24 percent lighter than corresponding core weights for .005 inch thick clad copper fins, tube diameter and wall thickness being the same.

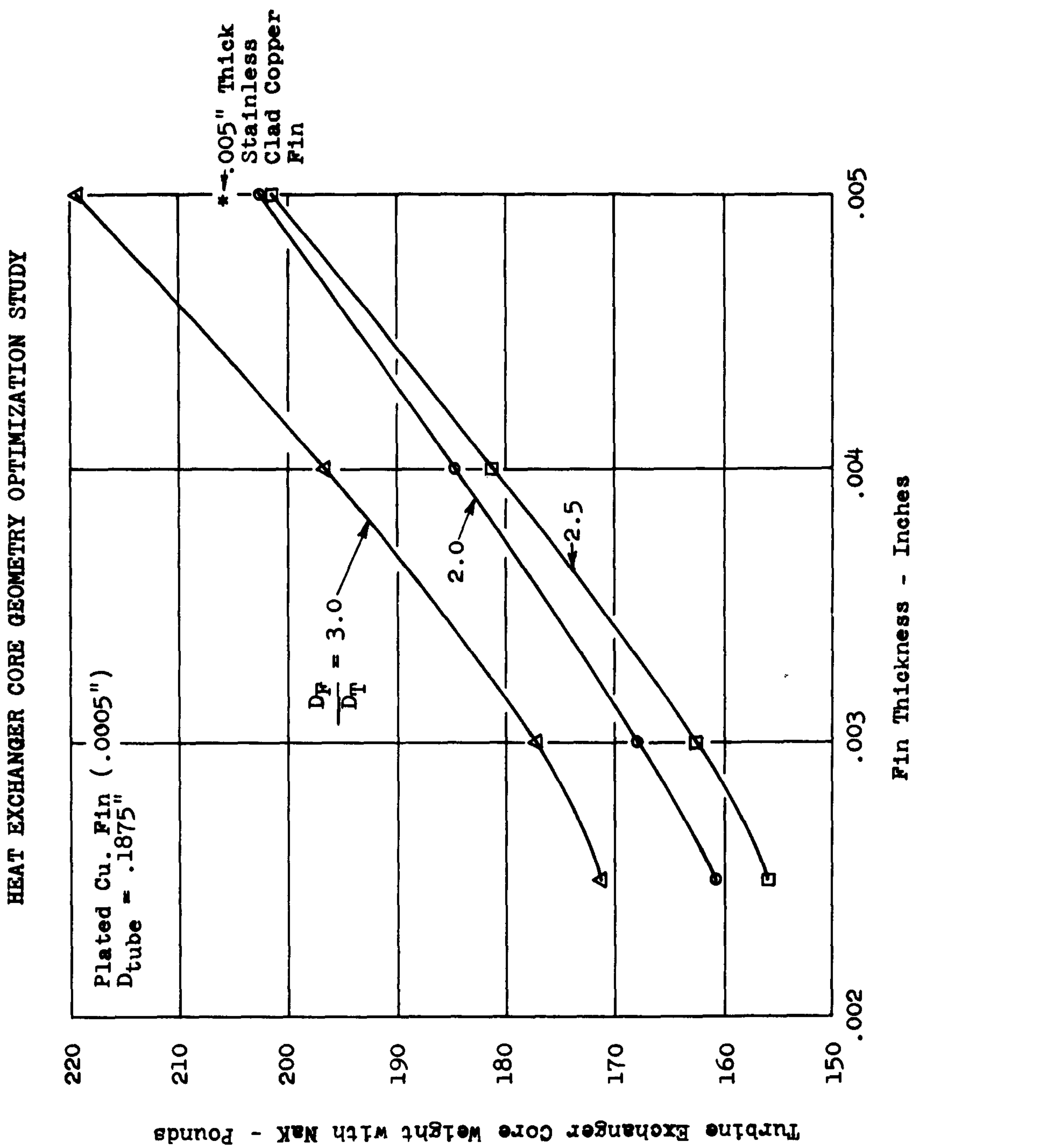

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Figure 4-1

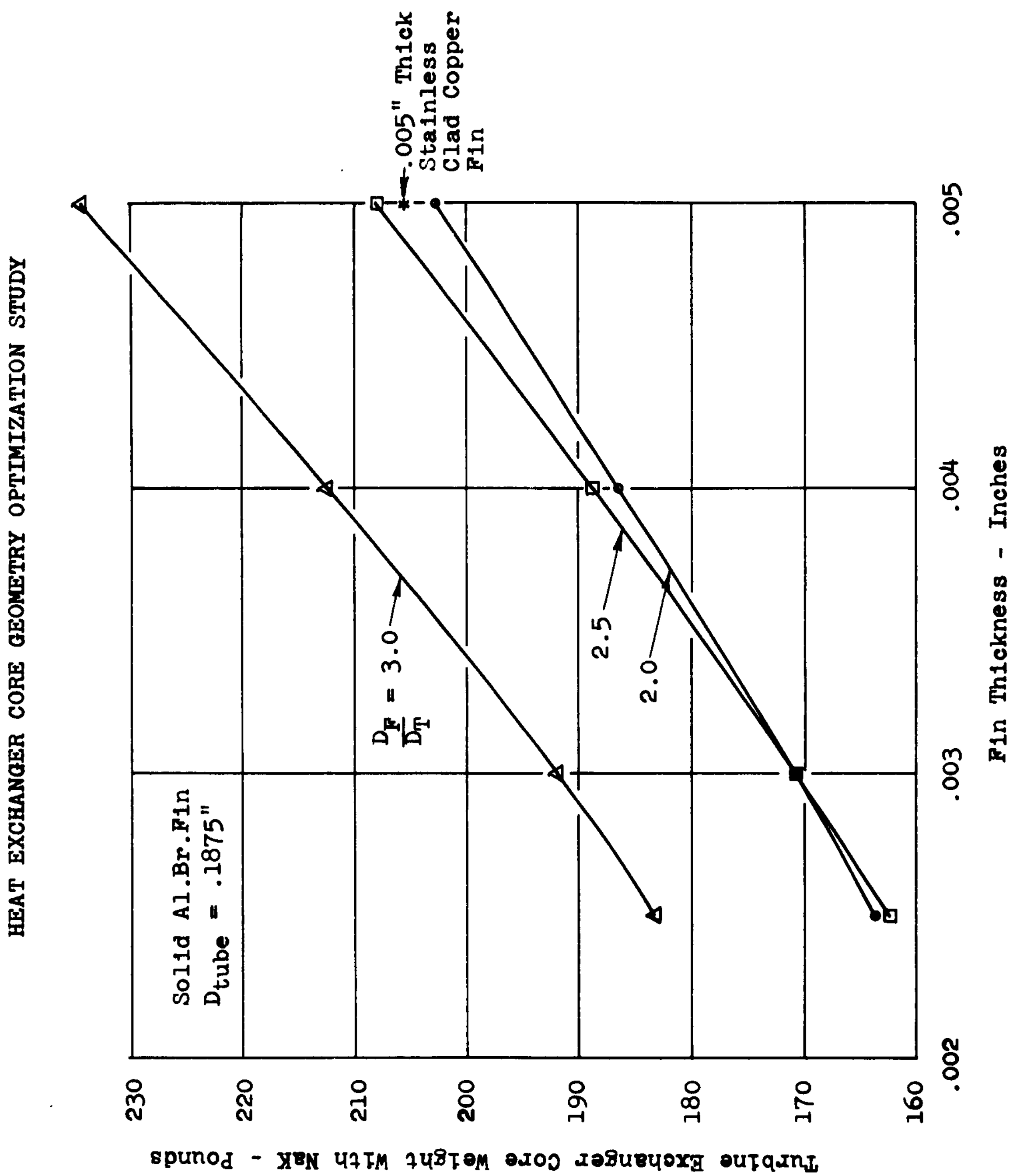

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Figure 4-2

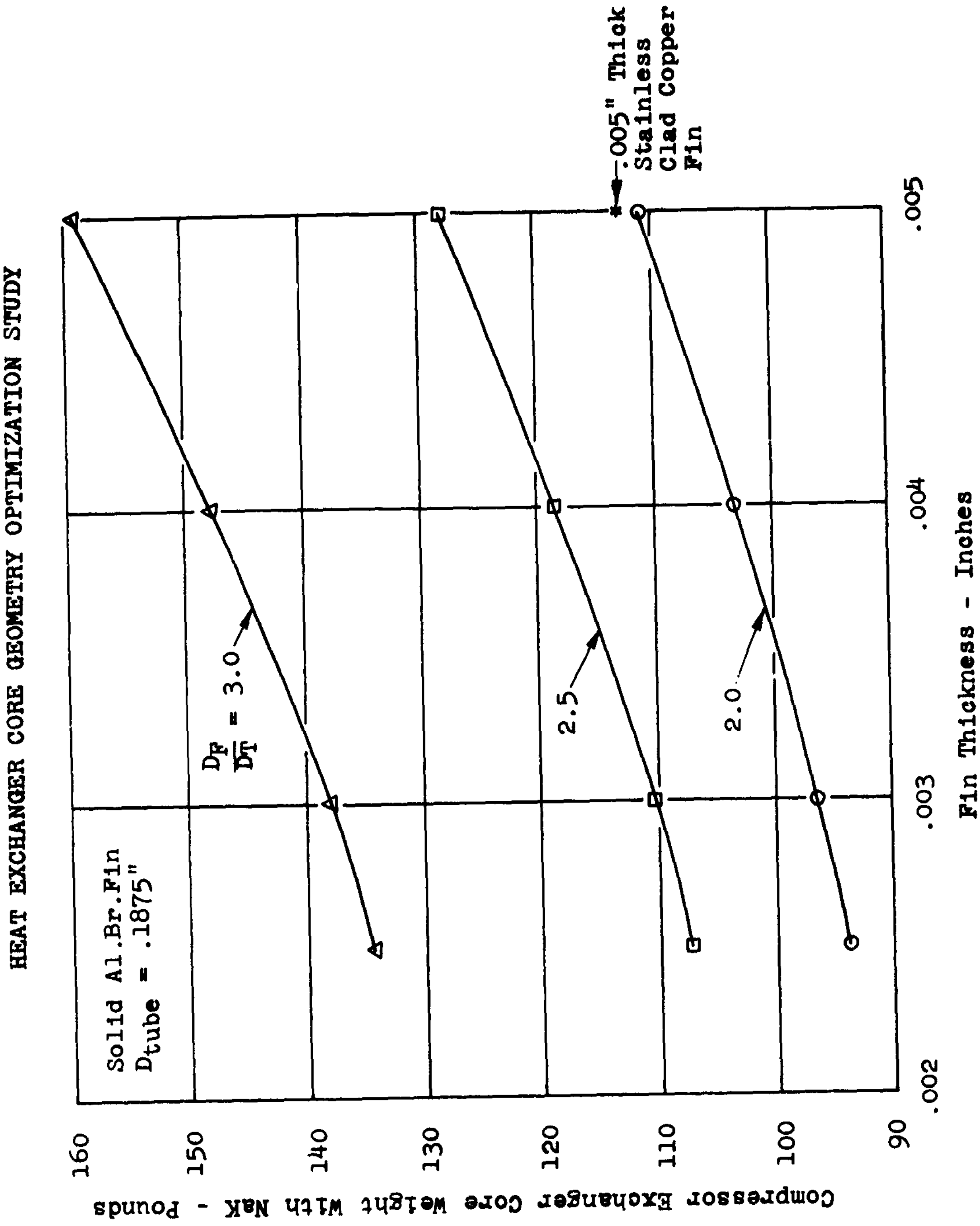
HEAT EXCHANGER CORE GEOMETRY OPTIMIZATION STUDY
Solid Al.Br.Fin
D_{tube} = .1875"
$\frac{D_F}{D_T}$ = 3.0
2.5
2.0
.005" Thick Stainless Clad Copper Fin
160
150
140
130
120
110
100
90
.002
.003
.004
.005
Fin Thickness - Inches
Compressor Exchanger Core Weight With NaK - Pounds

Figure 4-3

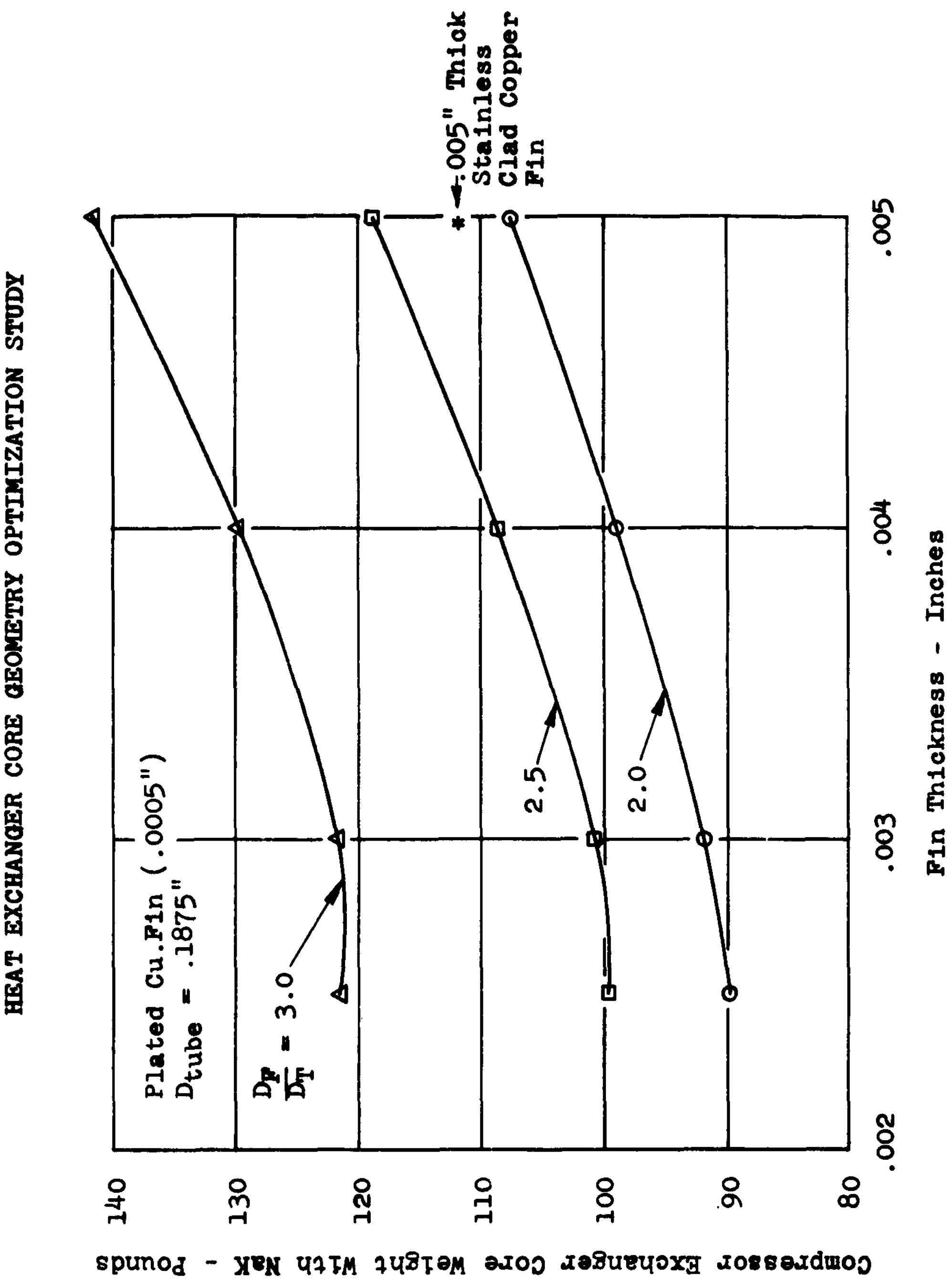

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Figure 4-4

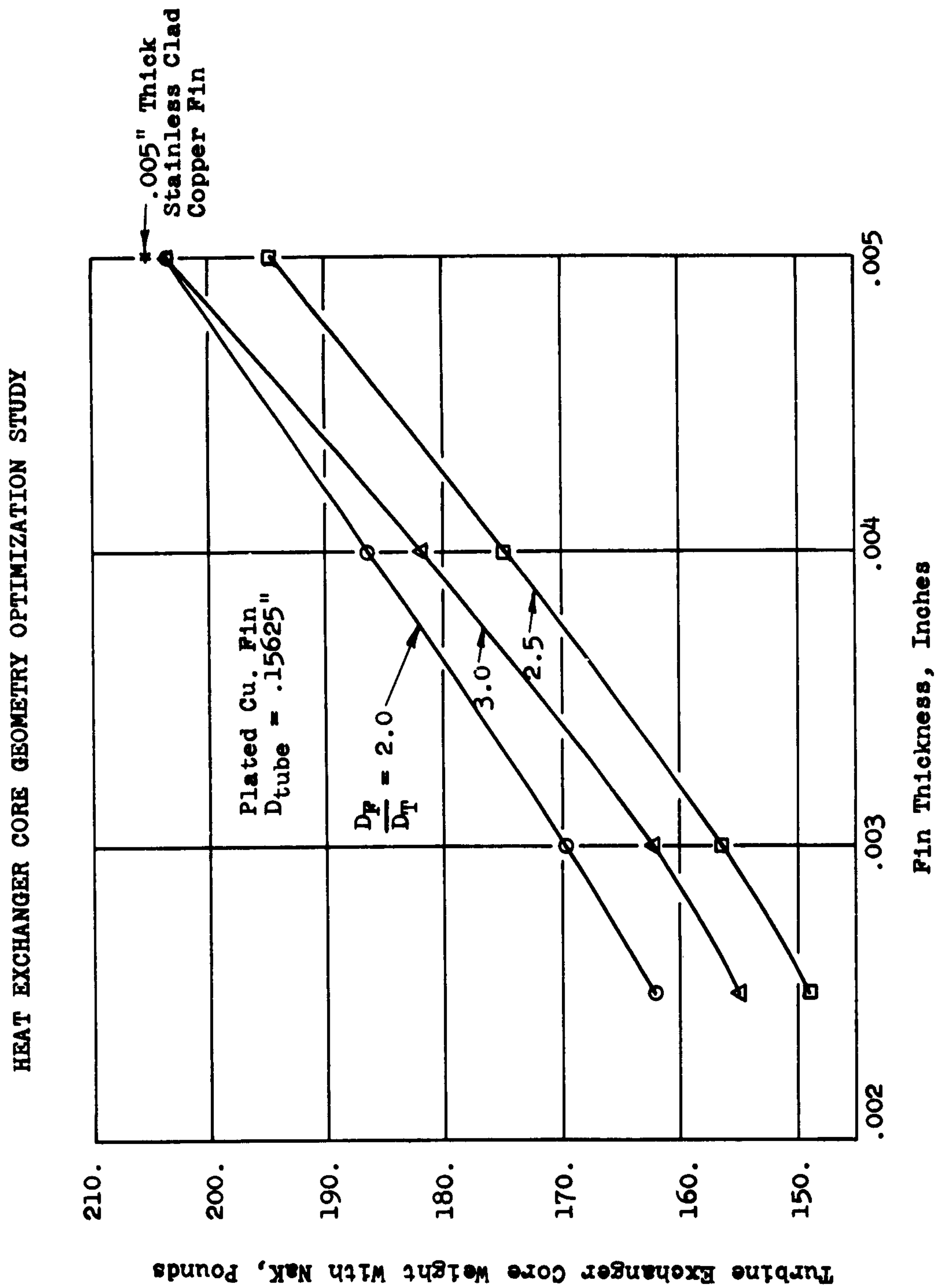

Figure 4-5

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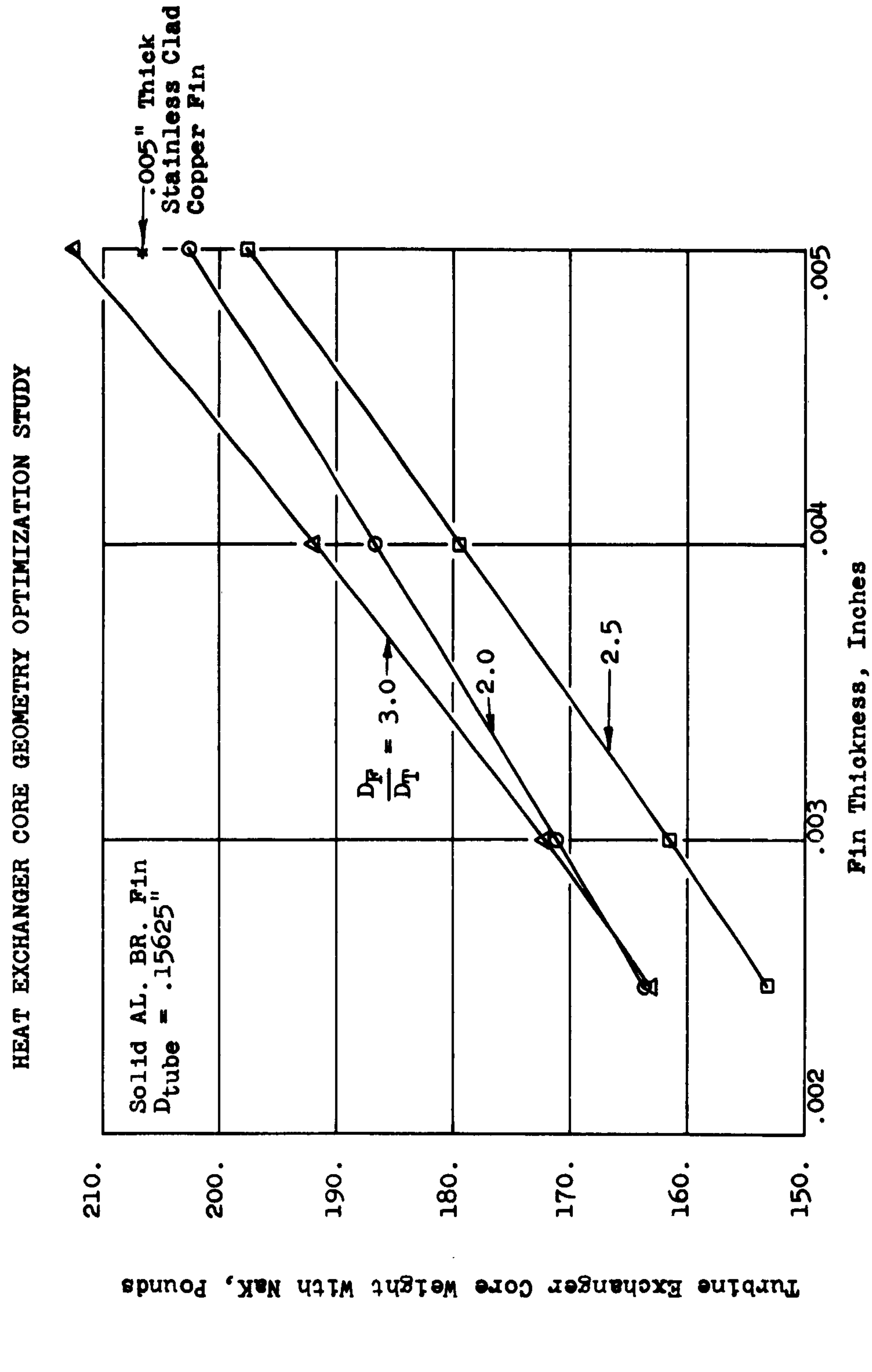

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Figure 4-6

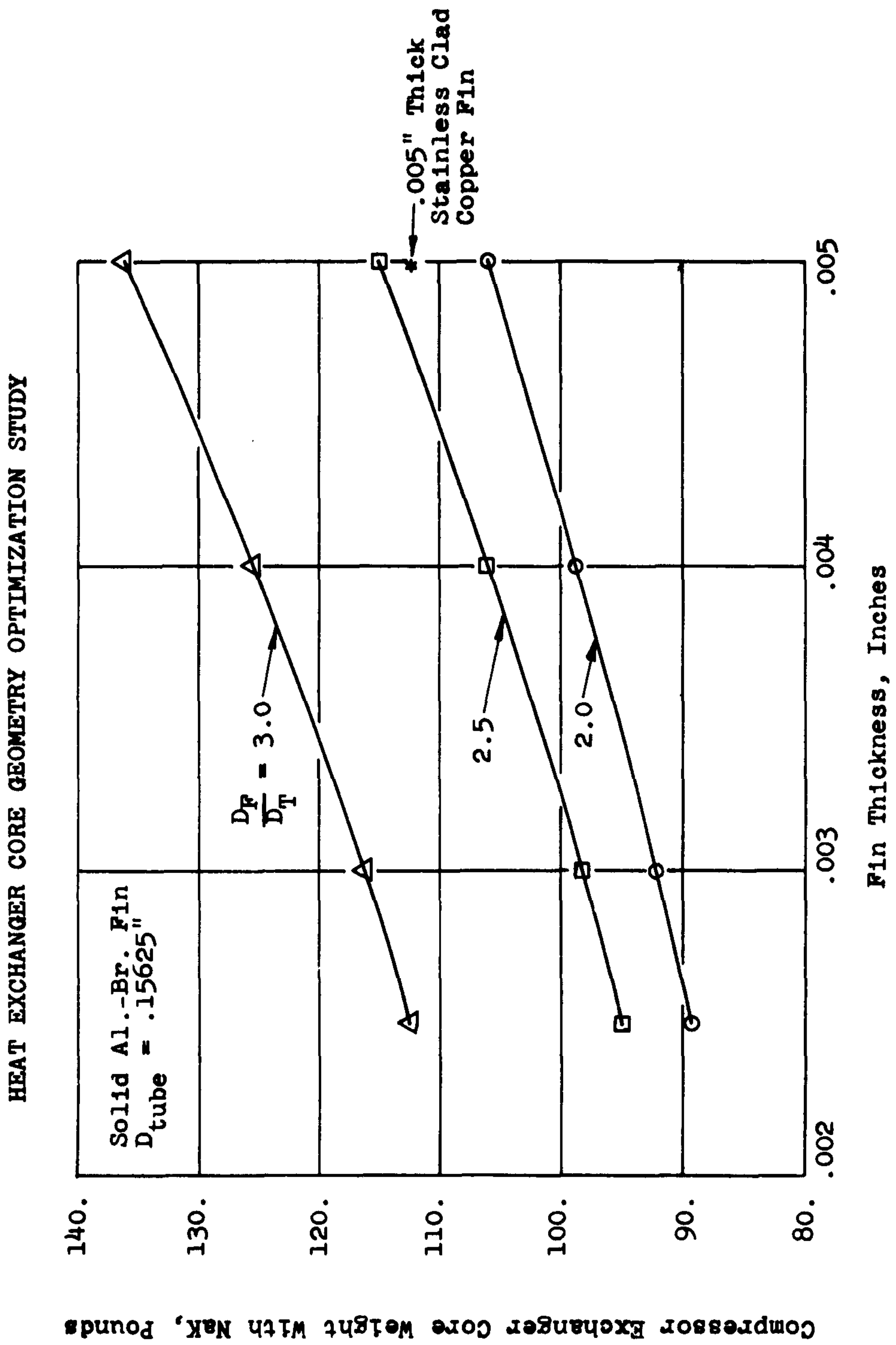
HEAT EXCHANGER CORE GEOMETRY OPTIMIZATION STUDY
Solid Al.-Br. Fin
D_{tube} = .15625"
$\frac{D_F}{D_T}$ = 3.0
2.5
2.0
.005" Thick
Stainless Clad
Copper Fin
140.
130.
120.
110.
100.
90.
80.
.002
.003
.004
.005
Fin Thickness, Inches
Compressor Exchanger Core Weight With NaK, Pounds

Figure 4-7

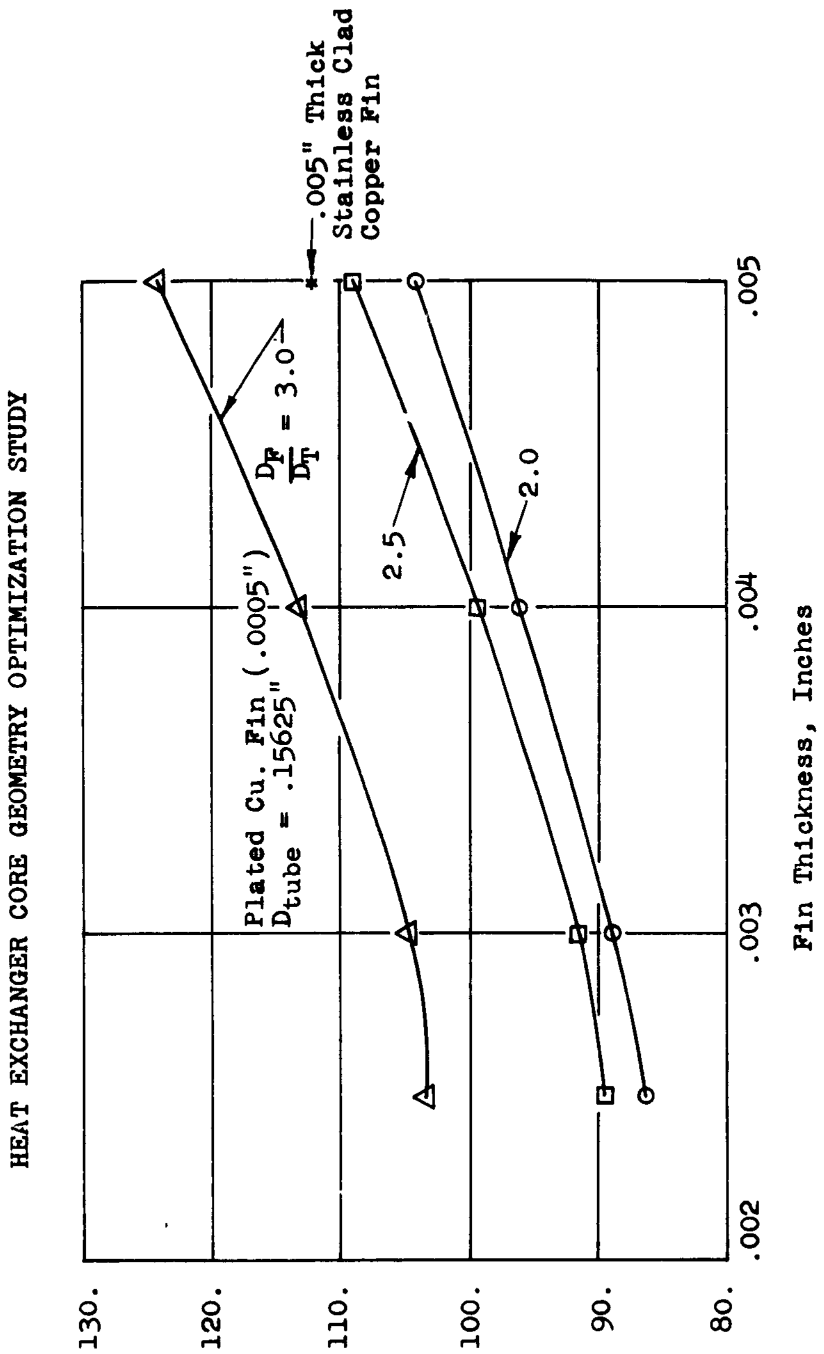

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Figure 4-8

V METALLURGICAL STUDIES

Current advanced heat transfer elements incorporate a 0.005" x 0.094" stainless clad copper fin with a spacing of 30 fins per inch, produced by spiral winding on a 0.1875" O.D. stainless steel tube (Fig. 5-1). Further reductions in the thickness of this fin material are precluded due to a lack of ductility in thin sections of this nature and possible discontinuities in the protective cladding. Another drawback to the utilization of a clad fin material is the necessity of protecting the edges from the corrosive and oxidizing environments encountered during engine operation. At present, protection is accomplished by spraying a nickel base braze material on the wound finned tube, but a weight penalty is incurred.

A. Materials

The optimum fin material should possess high temperature oxidation and corrosion resistance combined with an inherent high value of thermal conductivity, approaching that of copper at the intended fin operating temperature (600-1100°F). A literature survey indicated aluminum bronze (4 - 6% aluminum) and a zirconium/copper base alloy (Amzirc) were possible choices for an application of this nature. Amzirc has an excellent value of thermal conductivity (Fig. 5-2), but its oxidation resistance was unknown at temperatures above 800°F. The thermal conductivity of aluminum bronze is considerably less than that of pure copper at ambient temperature but the Oak Ridge National Laboratories has reported its value increases steadily with increasing temperature as depicted in Fig. 5-2. Heat exchanger core configuration studies using these data and actual engine conditions indicated that an aluminum bronze finned tube would be comparable, in terms of performance, to a clad copper finned tube. Oak Ridge also indicated that the 6% aluminum bronze alloy evaluated at the laboratory was oxidation resistant to within 70°C of its melting point. For purposes of obtaining a higher performance fin material, a 5% aluminum bronze alloy was selected for evaluation. It was postulated that the oxidation resistance of this alloy would be adequate for the intended application and an increase in the thermal conductivity would be realized due to the decrease in aluminum content.

B. Material Evaluation

Exposure of the promising materials for 100 hours in static air at 1200°F was selected as a screening test. The 5% aluminum bronze alloy incurred no harmful effects from oxidation as a result of this exposure treatment. Additional exposure under identical conditions, for up to 500 hours, did not significantly affect the subject alloy. Fig. 5-3 depicts a cross-section of the 0.005" thick aluminum bronze foil during various stages of exposure. Recrystallization is evident in the exposed sections, but no significant reduction in thickness or intergranular penetration has occurred. The zirconium copper alloy, on the other hand, sustained a total cross-sectional loss of 0.0045" due to oxidation after 100-hours exposure in static air at 1200°F. The oxide formed did not adhere to the parent metal and therefore, was not protective in nature. Since heat exchanger operating conditions are more severe than those encountered in the static exposure test, no further testing of this alloy was scheduled.

The primary barrier to further reductions in fin thickness is the lack of ductility of the clad materials. Previous experience has dictated that a minimum ductility of 28% elongation in six inches is required to successfully fabricate finned tubing of the dimensions previously described, by means of a spiral winding process. Attempts to wind an element with 0.0035" stainless clad copper fin material were unsuccessful due to a lack of ductility of this nature, which resulted in cracking and subsequent breaking of the strip during the precoiling and winding operations. Attempts to heat treat this stock to the required ductility were unsuccessful. In order to establish the feasibility of utilizing the 5% aluminum bronze in this fabrication process, the alloy was procured in "ribbon" form (0.003" thick, 3/32" wide). Tensile tests of the material in the as-received condition indicated a ductility of 2 - 3% elongation in 6". This low ductility was expected, however, due to the large amounts of mechanical deformation incurred in rolling the material to foil. Subsequent annealing treatments raised the ductility of the aluminum bronze ribbon above that required for spiral winding (Table 5-1). Of the three annealing temperatures tested (950, 1200, and 1700°F), 1200°F for five minutes in argon produced the highest ductility of 46% elongation in 6".

C. Oxidation Resistant Coatings

A parallel approach was adopted to establish the feasibility of coating OFHC copper fins for operation at design temperatures (up to 1200°F). The type of coatings to be evaluated consisted of the following: plated (electrolytic and electroless), vapor deposited, and diffusion. A screening test consisting of exposure at 1200°F for 100 hours in static air was selected for evaluation of feasible coatings. Small finned tube samples incorporating 0.005" thick OFHC copper fins, brazed to a stainless steel tube with a fin spacing of approximately thirty per inch, were fabricated to evaluate the various coatings.

D. Electrolytic Coatings

Several OFHC copper "washers", electrolytically plated with nickel and chromium, were subjected to the screening test to determine the susceptibility of the coatings to oxidation and cracking under thermal shock. Metallographic examination of the chromium plated samples revealed cracking in the as-plated sample which led to complete coating breakdown on the exposed fins (Fig. 5-4). Due to the inherent brittleness of the electrolytic chromium plate, it is believed that this cracking was caused during plating or subsequent handling operations. The electrolytic nickel plate exhibited sufficient ductility to withstand cracking of this nature, but subsequent exposure treatments resulted in isolated breakdown of the coating (Fig. 5-5). Since plating techniques of this type are applicable only to individual fins and not a final assembly, it is expected that coatings which can be applied to an assembled and brazed heat exchanger serpentine will preclude their use.

E. Vapor Deposited Coatings

Fin spacings of thirty fins per inch also severly limit the use of vapor deposited coatings. The strength and density of coatings vapor deposited on the sides of the fins would not be adequate to provide protection at heat exchanger operating temperatures for a substantial length of time. This lack of strength is due to the poor angle of incidence at which coatings of this nature would have to be deposited. Coatings of this type, however, would be useful in protecting the edges of a clad fin element, enabling the incorporation of tubes precoated with braze alloy in the fabrication process.

F. Electroless Nickel Plating

Several brazed finned tube samples were plated with an electroless nickel plate to a thickness of 0.0005" (Fig. 5-6A). Metallographic examination revealed that the plating operation had completely covered all the exposed surfaces, including the critical tip and base areas (Fig. 5-6B) of the fins. Exposure of similar samples for 100 hours at 1200°F induced localized cracking which resulted in subsequent penetration and peeling of the protective nickel plate. Superficial cracks were produced in a sample exposed only 15 minutes at 1200°F (Fig. 5-7). It was postulated that this phenomenon was caused by the inherent stress present in the protective nickel plate, combined with the thermal shock incurred by placing the sample in a hot furnace at 1200°F.

The ability to withstand thermal shock is a primary consideration in selection of an element designed for incorporation in a regenerator system and cannot be avoided. Electroless nickel, however, can be stress relieved at 600 - 700°F. Additional samples were therefore fabricated and stress relieved at 650°F for 30 minutes, prior to exposure. The electroless nickel plate on these samples was still intact after 500 hours exposure at 1200°F.

Metallographic examination of samples exposed at 1200°F revealed what appeared to be a eutectic Cu_3P phase. This phase formed as a result of the diffusion of phosphorous, inherently present in the electroless nickel plate (8%), into the copper at the exposure temperature. Exposure at a lower temperature (900°F) for an identical period of time, significantly reduced the formation of the subject phase (Fig. 5-8). In an attempt to inhibit the diffusion of phosphorous into the copper a "flash" of electroless gold was applied to the samples prior to the nickel. Exposure of these samples revealed that the intermediate gold coating affected the rate of Cu_3P precipitation, but did not prevent it.

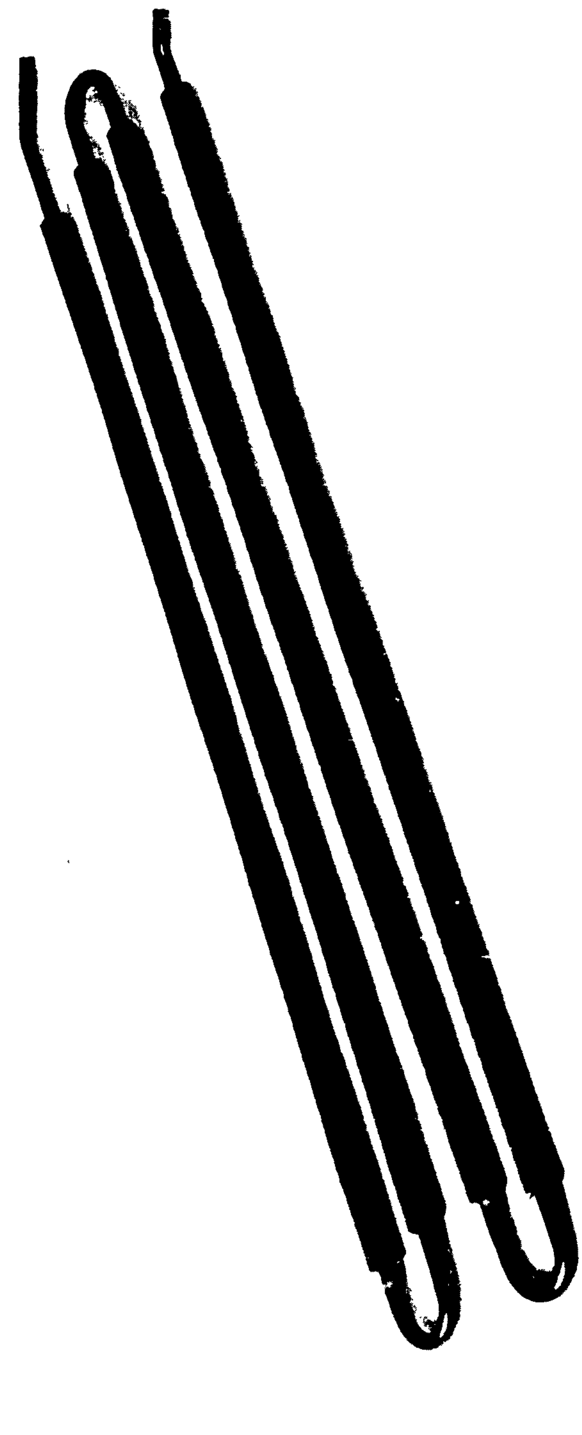
The effect of the precipitated Cu_3P phase on the thermal efficiency of the fin is indeterminate and actual measurements would have to be taken if the electroless nickel coating were to be considered for use in a liquid metal regenerator. Examination of a portion of the copper-phosphorous phase diagram (Fig. 5-9) suggests that eutectic melting will occur if this system is subjected to an operating temperature in the vicinity of 1300°F.

ANNEALING OF 0.003" ALUMINUM BRONZE (5%) STRIP

Heat Treatment	Test No.	Elongation in 6"	
		In.	%
As Received	1	0.125	2.1
	2	0.18	3.0
950°F, 5 min.	1	1.125	18.8
	2	1.5	25
1200°F, 5 min.	1	2.75	46
	2	2.75	46
1700°F, 5 min.	1	1.69	28.2
	2	1.75	29.2

Note: All heat treatments performed in Argon and air cooled.

Table 5-1



Incorporates a 0.005" thick x 0.094" high stainless clad copper fin with a spacing of 30 fins per inch. Spiral wound on a 0.1875" O.D. stainless steel tube.

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Figure 5-1

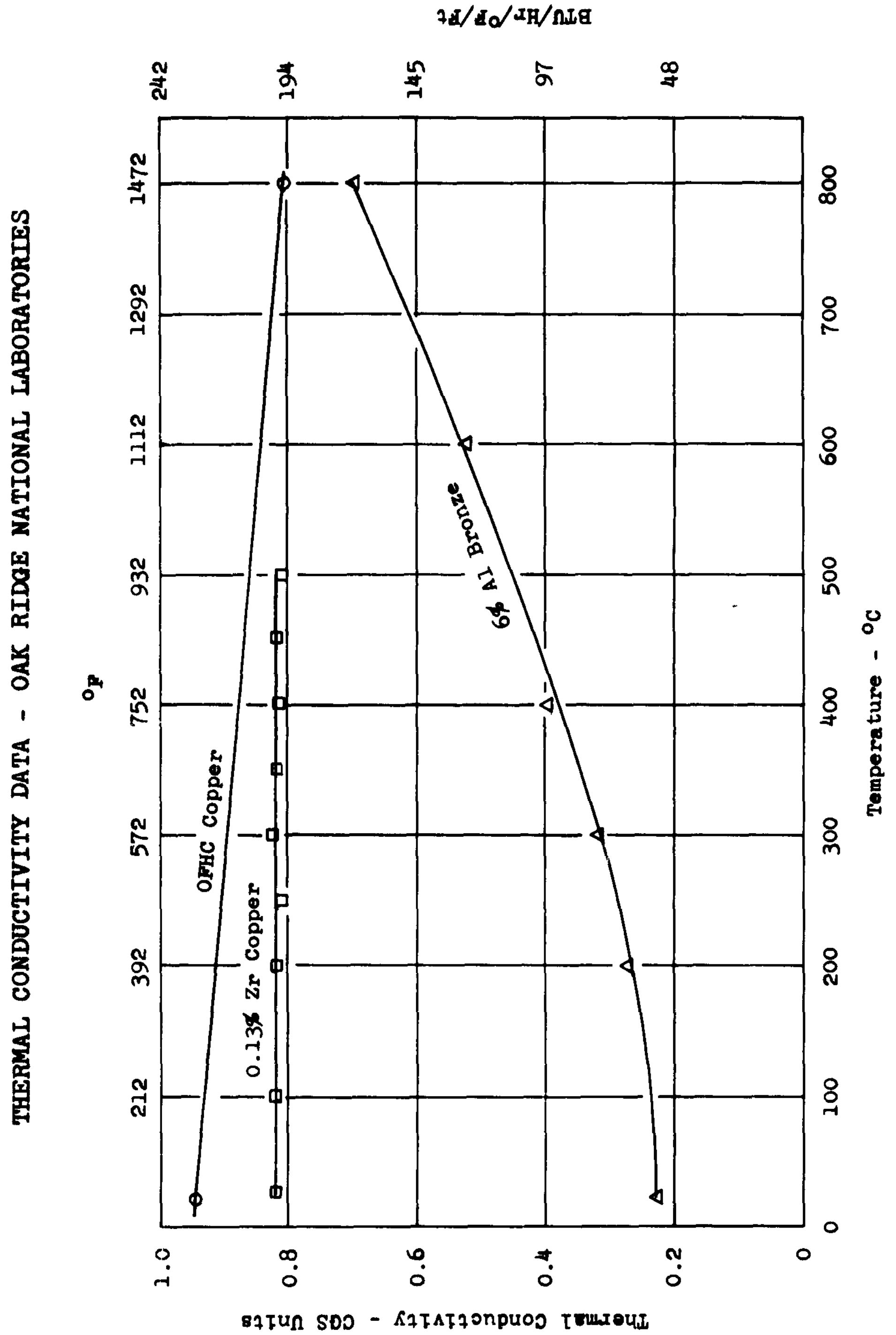
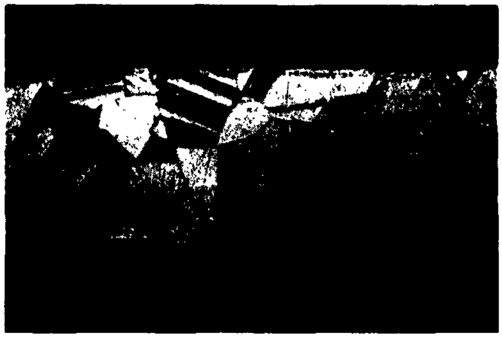

THERMAL CONDUCTIVITY DATA - OAK RIDGE NATIONAL LABORATORIES
°F
212
392
572
752
932
1112
1292
1472
BTU/Hr/°F/Ft
242
194
145
97
48
OFHC Copper
0.13% Zr Copper
6% Al Bronze
1.0
0.8
0.6
0.4
0.2
0
Thermal Conductivity - CGS Units
0
100
200
300
400
500
600
700
800
Temperature - °C

Figure 5-2

PN 50677 Mag. 200x
As Rolled



PN 50678 Mag. 200x
Exposed 112 hours

PN 50679 Mag. 150x
Exposed 500 hours

0.005" thick aluminum bronze foil before and after exposure at 1200°F in static air.

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Figure 5-3

Mag. 200X

PN 50595

Ferric Chloride Etch
As Plated

Mag. 200X

PN 50596

Ferric Chloride Etch
Exposed at 1200°F for 100 Hrs. in Air

Electrolytic chromium plate on 5 mil thick copper washers before and after exposure at 1200°F.

Figure 5-4

PN 50597 Mag. 200X

Ferric Chloride Etch
As Plated

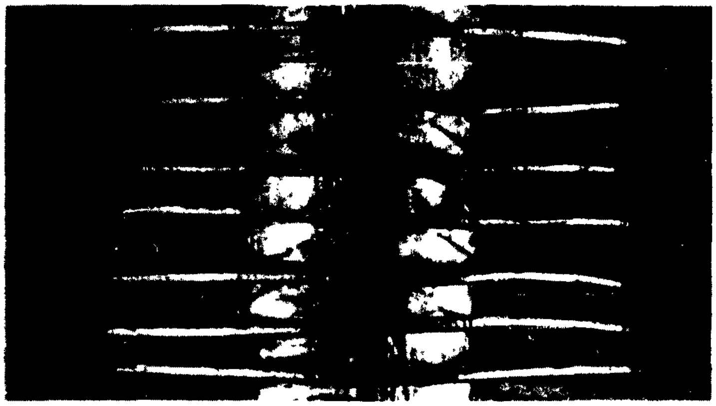
PN 50598 Mag. 200X

Ferric Chloride Etch
Exposed at 1200°F for 100 hrs. in Air

Electrolytic nickel plate on 5 mil thick copper washers before and after exposure at 1200°F.

5521

Figure 5-5



Mag. 8X

A

$FeCl_3$ - HCl Etch

Mag. 200X

B

Electroless nickel plate on an OFHC copper finned tube sample. Note the excellent coating coverage around the flange at the base of the fin (B).

5530

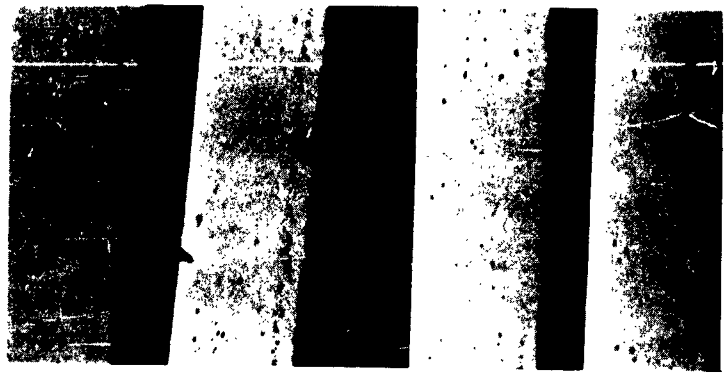
Figure 5-6

$FeCl_3$ Etch Mag. 200X

Cracking of the electroless nickel plate after 15 min. exposure at 1200°F.

5527

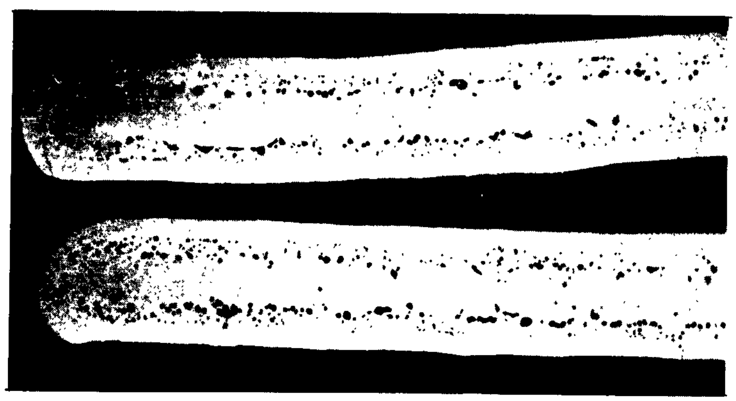
Figure 5-7



A

Mag. 100X

Exposed 100 hrs. @ 900°F



B

Mag. 100X

Exposed 100 hrs. @ 1200°F

Photomicrographs depicting the formation of Cu_3P at the electroless nickel - OFHC copper interface. Note the decrease in the amount of phase present and the absence of apparent eutectic melting at the lower exposure temperature (900°F).

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Figure 5-8

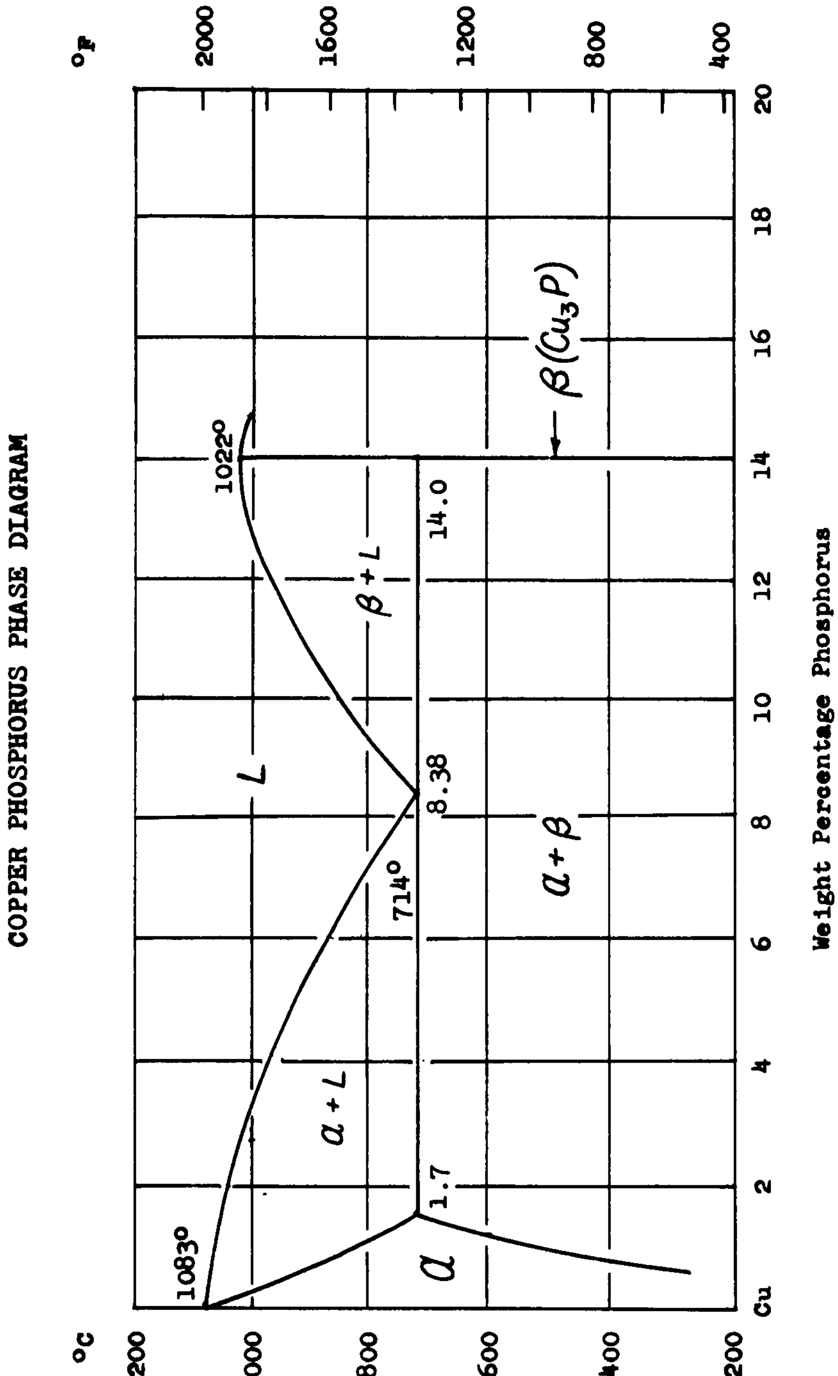

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Figure 5-9

VI FABRICATION STUDIES

Currently available heat transfer elements in sizes applicable to flight type heat exchangers are produced by means of a spiral winding fin material on tubes. The most promising alternate method of fabrication yields a disc fin type heat transfer element. Fabrication of disc fin elements involved developing special manufacturing processes for mounting and bonding large numbers of closely spaced, small diameter, thin fins onto tubing. One of the major difficulties encountered in making a heat transfer element of this type was the handling of the "foil-like" fins without distortion and maintaining the spacing of such fins until they were bonded to the tube. On the other hand, the design had the distinct advantage of being particularly well suited to low ductility fin materials and to thin wall tubing, since it did not distort the tube wall. The design further allowed wide latitude in the ratio of fin diameter to tube diameter. The potential advantages of disc fin elements led to an investigation of production methods to position fins. The inclusion of temporary spacer material between fins was selected as the most promising approach.

A. Spacer Materials

The function of the spacer material in the fabrication of disc fin type heat transfer elements was to maintain the uniform spacing of the fins until they were bonded to the tube. Spacers of this nature may be classified in the following three categories:

1. Leachable: This type of spacer would be in the form of a "washer", fabricated from a leachable ceramic material. The spacers would be leached out after brazing.

2. Mechanical: A spacer of this nature would be "U" shaped, fabricated from a metallic or ceramic material. The spacers would be removed after brazing and could be used a number of times.

3. Expendable: Expendable spacers would also be "washer" shaped and could be fabricated from a number of materials (i.e., cardboard, fiberboard, plastic, etc.). They would disintegrate during the brazing operation leaving little or no residue.

Preliminary investigation of the three types of spacer materials indicated that the cost of utilizing leachable or mechanical spacers would be excessive. Both the initial material costs and the subsequent handling costs incurred by utilizing materials of this nature would be prohibitive. Because of the inherent disadvantages associated with the leachable and mechanical spacers, effort was concentrated on the use of expendable spacer materials.

Initial brazing trials were conducted utilizing 0.005" thick x 0.4375" O.D. aluminum bronze and OFHC copper fins. Cardboard, fiberboard, and asbestos spacer materials were evaluated. Of this group, fiberboard spacers yielded the most promising finned tube sample, leaving a loose carbonaceous deposit after brazing. This deposit was easily removed by washing with water and a fine bristle brush, leaving the fins only slightly discolored.

It was suggested that thermoplastic materials would vaporize and/or burn off more readily at the brazing temperatures. In addition, they would be easier to handle and bond to the fin material, especially in production quantities. "Teflon", polyethelene, and "Delrin" were selected for evaluation. All the plastic materials appeared to produce finned tube samples with low fin distortion and good fin alignment. The light ash remaining after brazing was easily blown away with an air hose. Fin discoloration was evident, and attempts to clean the tubes utilizing mechanical and chemical techniques were unsuccessful. It was believed that this discoloration was produced by some type of reaction between the brazing flux and the spacer material as it melted and vaporized during the brazing cycle. The discoloration was found to be shallow and will have no effect on heat transfer. To further evaluate the production capabilities of the three plastic spacer materials, several sheet samples were made consisting of 0.003" thick aluminum bronze sheet bonded to plastic sheet with a commercial adhesive. These samples were then processed through the fin stamping dies to determine the feasibility of stamping the bonded sheet. With the polyethelene-aluminum bronze sample the plastic proved to be too soft and it was very difficult to produce a clean cut. This condition led to fouling of the dies, making it inadvisable to use this material in a production set up. Difficulty was also encountered with the sample incorporating the Teflon sheet. This plastic inhibited the formation of the "flanges" on the I.D. of the fin. Brazing trials indicated that without these flanges it was impossible to maintain the desired fin alignment and joint efficiency. The Delrin-aluminum bronze sample, on the other hand, did not present any problems during the stamping operation. On the basis of this evaluation, brazing trials were continued utilizing fins stamped from 0.003" thick aluminum bronze sheet bonded to 0.030" Delrin sheet.

B. Brazing Development

Initial brazing trials for the evaluation of spacer materials were performed using Handy & Harman "Braze ETX" and H & H type A-1 flux. The braze was a commercial silver solder especially recommended for aluminum bronze. The samples were in the form of 0.1875" O.D. stainless steel tubes approximately one inch long. The braze was preplaced on the tube by means of a "tinning" operation with an acetylene torch.

The fins were then placed on the tube with the aid of spacers and the entire assembly was inserted into a hydrogen atmosphere furnace.

The "tinning" method of applying the braze alloy was adequate for small laboratory samples but could not be adopted as a production process. The coating produced was inconsistent in thickness, especially if applied to long pieces. The following methods were, therefore, devised to coat the tubing with a silver-copper eutectic braze alloy:

1. The braze alloy was procured in fine power form, mixed with a flux, and painted on the tube along the desired length. The prepared tube was then run through an induction coil which melted and flowed the braze alloy on the tube. Refinement of this technique has produced uniform coatings approximately 0.001 inch thick.

2. Silver and copper were electrodeposited separately on the tube to the desired thickness. The amount of each constituent was controlled so that the final coating contained approximately the eutectic composition of 70% silver and 30% copper. Fins were placed on the tube and the assembly was heated to 1450°F for 10-15 minutes. The two plates alloyed and eutectic melting resulted, which brazed the fins to the tube. Brazing primarily occurred under the flanges on the I.D. of the fin (Fig.6-1). Of the two methods, electrodeposition was preferable because it was considered to be adaptable as a batch process and easier to control.

In addition to the Ag-Cu plating and brazing technique described above, samples were procured with a gold-copper eutectic alloy plate. Interest was expressed in this alloy as a high temperature, oxidation-corrosion resistant braze material. The Au-Cu composite plate required less time at the brazing temperature and samples were successfully brazed in 5-7 minutes at 1750°F. The effect of the higher brazing temperature on the corrosion resistance of the aluminum bronze fin material has not been determined at the present time and further investigation would be warranted.

Gold-nickel alloy systems may also be of interest for brazing finned tubes but application of this alloy to the tube may be difficult unless cladding techniques can be applied.

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1. The braze alloy was procured in fine power form, mixed with a flux, and painted on the tube along the desired length. The prepared tube was then run through an induction coil which melted and flowed the braze alloy on the tube. Refinement of this technique has produced uniform coatings approximately 0.001 inch thick.

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C. Spiral Winding Studies

Current materials and fabrication techniques, employed in the manufacture of spirally wound finned tubes, imposed substantial limitations on the performance versus weight of liquid metal systems utilizing these elements. The primary problem areas were the following:

(1) The steady decrease in ductility, incurred as the thickness of the fin material (stainless clad copper) was progressively reduced,which prevented the use of this fin material in thicknesses less than 0.005".

(2) Grooving of the tube to position the fins resulted in distortion of the tube wall. The amount of distortion allowable dictated the wall thickness of the tubing. Tube distortion increases the resistance to the flow of liquid metal,and therefore, is undesirable.

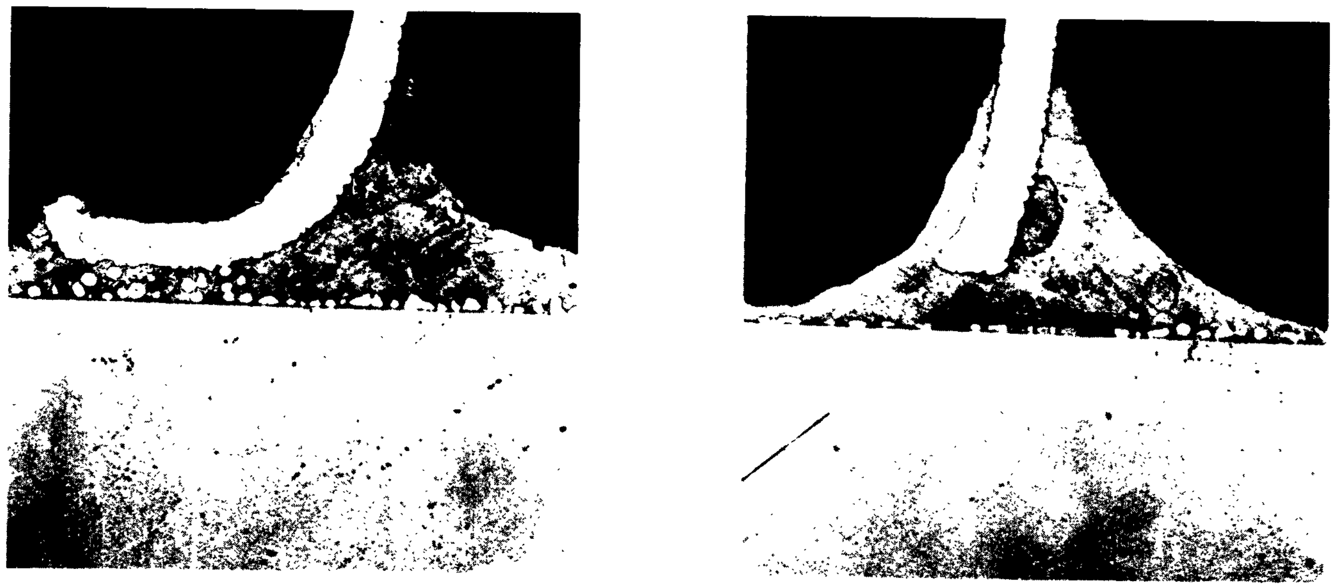
(3) The stainless clad copper fin material required protection of the edges from the corrosive and oxidizing environments encountered during service. Protection was accomplished by spraying the braze material on the finned tubes, but resulted in an additional weight penalty.

Investigations to reduce these problem areas were severely limited because available capabilities had to be devoted to production of heat transfer elements used in the fabrication of the heat exchangers evaluated under a separate and concurrent investigation of liquid metal regenerator systems. However, sufficient work was performed to demonstrate the feasibility of using aluminum bronze as a fin material to overcome the limitations described above.

Sample finned tube elements have been successfully made by winding 0.003" thick aluminum bronze fin stock, in the annealed condition, without the aid of positioning grooves. Methods of bonding the spiral wound aluminum bronze fins by brazing were not investigated because of cost and time limitations of this program. Precoating the tubes with braze alloy(as was demonstrated in the disc fin investigation) appears to be a logical approach,as well as the application of a braze material,in wire form, spiral wound between the fins.

Spiral wound fins made by convoluting the inner edge of the fin material were not investigated because current manufacturing practice did not produce tubes of appropriate size. There was also some concern as to the susceptibility of such fins to fouling. Recent experience with high velocity gas streams indicated that fouling may not be a problem. Further consideration of convoluted finned tubes is warranted.

It is expected that convoluted finned tubes could give higher performance than flat wound fins when compared on an equal weight basis because of higher gas heat transfer rates. Figure 7-2 depicts a copper fin tube of this type in the smallest size currently available (.250 tube). Discussion with manufacturers of such finned tubes indicate the possibility of going to smaller diameter tubes and closer fin spacing. The material and brazing techniques developed under this program appear to be applicable to this type of tubing. The susceptibility to fouling under engine conditions must be investigated.



A B

Mag. 100X $FeCl_3$ Etch

Typical braze joints obtained at the base of 0.003" thick aluminum bronze fins. The flange at the base of the fin (A) covers approximately 80% of the fin I.D. and is divided into three segments.

5541

Figure 6-1

Mag. 4X

Convoluted finned tube. 0.005" thick OFHC copper wound on a 0.025" O.D. stainless steel tube. No positioning grooves or braze alloy have been used to maintain fin spacing and alignment.

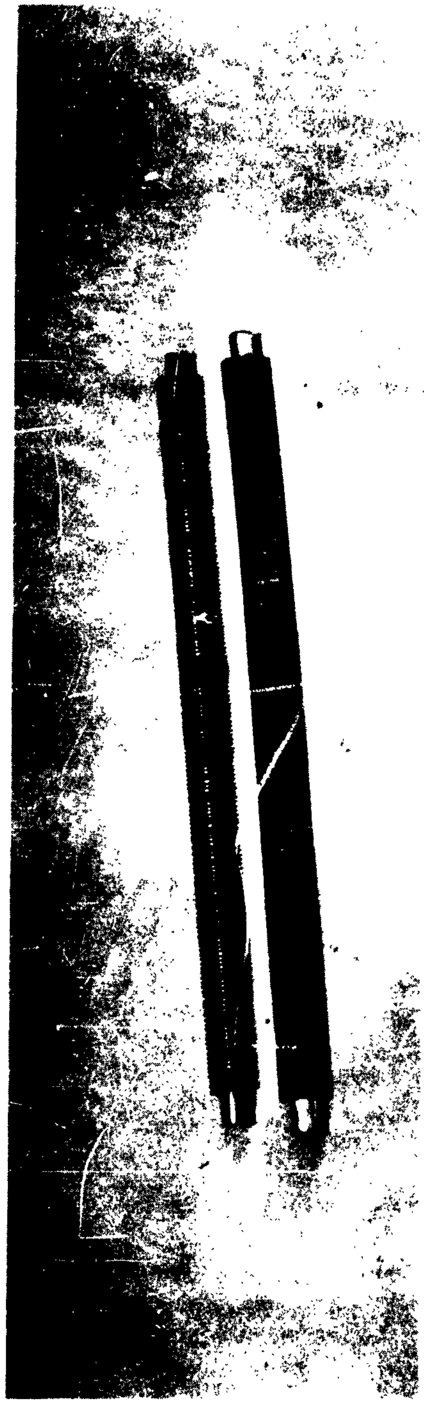
5523

Figure 6-2

VII FABRICATION OF SAMPLE HEAT EXCHANGER

In order to prove the developed fabrication technique on a semi-production basis a sample 6 in x 6 in x4 in single pass heat exchanger was fabricated employing 0.003" thick x 0.375" O.D. 5% aluminum bronze fins, with a fin spacing of 30 per inch along a 6" tube length. The stainless steel tube wall thickness was reduced from the current 0.015" to 0.012". The silver-copper plating and brazing technique, described in the previous section, was used in the fabrication of the majority of the finned tubing. Approximately one-quarter of the tubes in the heat exchanger consisted of copper clad stainless steel tubing with 0.001" of silver plated over the cladding. No significant difference in brazing behavior was noted between the two methods of braze application.

Aluminum bronze strip (0.003" thick) was bonded to 0.030" thick Delrin plastic strip, using a double adhesive tape. Fins were then stamped from this composite and subsequently stacked on the braze coated tubing. A total plating thickness of approximately 0.0025" was used for this application. The stacked tubes were then brazed in a dissociated ammonia atmosphere furnace for 15 minutes at 1450-1500°F. The carbonaceous deposit remaining after brazing was blown away with an air hose and the tubes were mechanically cleaned by brushing with a fine-bristled brush and warm water in a direction parallel to the fins. Figure 7-1 shows a typical finned tube element prior to brazing (foreground), and after the cleaning operation. The brazed elements (99 total) were then assembled, expanded, and welded into headers. It should be noted that no difficulties were encountered in effecting a sound tube-to-header joint with the 0.012" wall tubing. Figure 7-2 depicts the assembled and welded heat exchanger. The use of 0.012" wall tubing instead of 0.015" wall tube produces a further 9% weight reduction in the total finned tube weight. Thinner wall tubes are feasible on the basis of finning techniques and lower internal pressure loads.

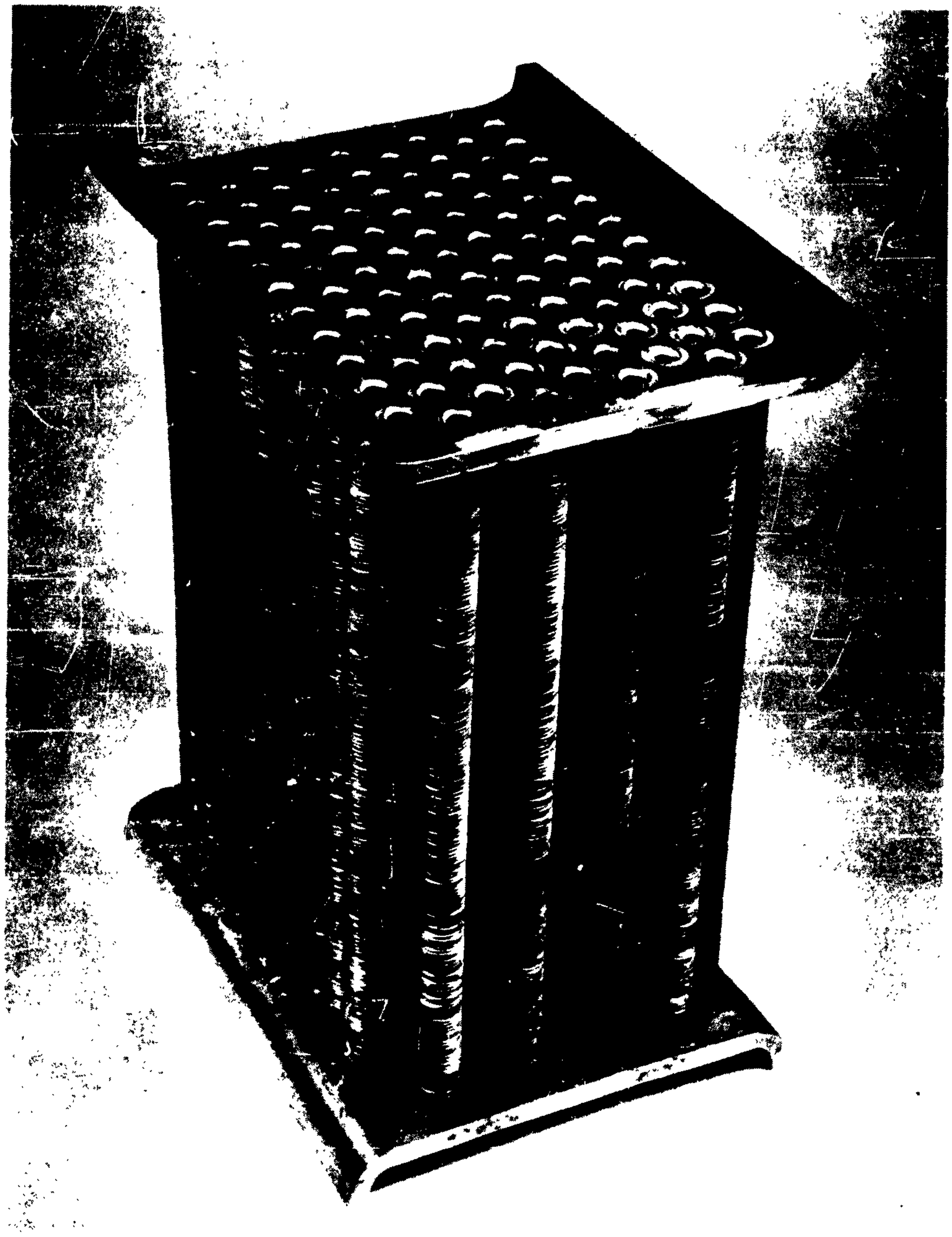


Upper - Disc finned tube after brazing and cleaning.

Lower - Disc finned tube with expendable spacers before brazing.

5535

Figure 7-1



SAMPLE HEAT EXCHANGER

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Figure 7-2

VIII RESULTS & DISCUSSION

Demonstration quantities of finned tube heat transfer elements for liquid metal heat exchangers have been made which are 30% lighter than those currently available when compared on the basis of equal size and equal performance. Further weight savings, based on equal performance, are possible by changes in geometry and in size of the heat transfer elements. These gains in performance are derived from metallurgical, analytical, and fabrication findings described below.

(1) Metallurgical investigations have demonstrated that aluminum bronze (5% aluminum, 95% copper) has good oxidation resistance at operating temperatures likely to be encountered in liquid metal regenerator systems for advanced turboprop engines. This property plus its relatively high thermal conductivity at operating conditions makes aluminum bronze an excellent fin material for finned tube heat transfer elements of liquid metal heat exchangers.

(2) The high ductility of aluminum bronze obtained by heat treatment has made possible the forming of this material into spiral wound fins of thicknesses and diameters appropriate for high performance finned tube heat transfer elements.

(3) Aluminum bronze can be bonded to stainless steel tubes by silver-copper, gold-copper, and gold-nickel braze alloys, of eutectic composition.

(4) Optimization studies show that maximum performance versus weight is gained by utilizing the thinnest fins that can be fabricated.

(5) The heat transfer characteristics of the heat exchangers indicate optimum performance versus weight is obtained by a 2:1 fin diameter to tube diameter ratio in the compressor exchanger, and a 2.5:1 diameter to tube ratio in the turbine exchanger for sizes considered most practical at this time.

(6) Grooves for positioning the fins can be eliminated in spiral wound finned tubes allowing the use of thinner wall tubes without incurring distortion in the tube wall.

(7) A new fabrication method for manufacturing disc fin tubes by use of expendable spacers for fin alignment and spacing during the brazing operation has been developed and appears economical.

(8) The new fabrication method imposes no limits on tube wall thickness. Therefore, the thinnest wall tube can be used consistent with operating conditions.

(9) The new fabrication method imposes no limits on fin to tube diameter ratio. Therefore, further optimization of heat transfer elements for each heat exchanger can be made consistent with liquid metal pumping requirements.

(10) The new fabrication method imposes no ductility requirements. Therefore, fin materials formerly considered impractical because of low ductility, such as .003" stainless steel clad copper, are feasible.

(11) Significant weight reduction for equal performance can be obtained by increasing the number of fins per inch of tube from 30 to a maximum yet to be determined by fouling tests.

(12) Electroless nickel plating provides durable oxidation protection for copper fins and can be applied in uniformly thin layers on finned tubes. However, the migration of phosphorus, inherent in the plating process, may have a detrimental effect on the thermal conductivity of the fins.

(13) Vapor deposited and electrolytic coatings investigated were unsatisfactory for protecting copper fins. However, the broad scope of this field and possible refinements in techniques warrant further efforts before conclusions can be made on coated fins.

(14) A practical fabrication technique for making thin tapered fins was not conceived during this investigation.

IX RECOMMENDATIONS

The limited scope of this study has made necessary the omission of several areas of investigation considered relative to further increasing performance versus weight of the heat transfer elements. Also efforts to determine practical limits of sizes and materials under actual service conditions have been restricted. In view of the potential of liquid metal regenerators for turboprop and turboshaft engines and the vital function of the heat transfer elements in such systems the following recommendations are made.

(1) Continue investigations of braze materials for bonding fins to tubes.

(2) Investigate brazing techniques for bonding spiral wound fins to tubes.

(3) Fabricate full length disc fin tube serpentines for manufacturing and performance evaluation.

(4) Operate liquid metal loops containing advanced heat transfer elements under engine conditions.

(5) Investigate the practical limits of fin spacing by long term fouling tests.

(6) Investigate improvements in heat transfer performance by convoluted fins and determine their susceptibility to fouling.

(7) Investigate the effect of phosphorus migration from electroless nickel plating on the thermal conductivity of copper fins.

(8) Conduct further investigations on protective coatings for copper fins.